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FOR

LOUDSPEAKER HORN AND METHOD FOR CONTROLLING GRATING LOBES IN A LINE ARRAY OF ACOUSTIC SOURCES

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Cross-Reference to Related Applications

This application claims the benefit of provisional application 60/448,911, filed February 21, 2003, and provisional application 60/452,975 filed March 7, 2003.

Background of the Invention

[001] The present invention generally relates to loudspeakers that utilize aligned acoustic power sources ("line arrays") and to the problem of undesirable grating lobes produced by line arrays. The invention particularly involves a horn structure, and a method for which can be used with multiple aligned drivers to control normally occurring grating lobes produced by the driver alignment.

[002] Line arrays are well known for their directional characteristics and ability to project acoustic power from multiple acoustic power sources over large distances. However, the disadvantage of line arrays is that grating lobes develop when the distance between the acoustic sources of the array is one wavelength or larger. To achieve a highest possible operating frequency and high output power without grating lobes, one needs to use a large number of very small sources. Increasing the number of elements increases the number of parts and connections, which makes manufacturing difficult. It is also difficult to obtain the necessary power out of very small transducers.

[003] Currently, there are many variations on the line array. Most variations focus on changing the signal that goes to each element. Line arrays have been made where the signal

magnitude, signal phase, and signal frequency content are altered for each element in the array. More often than not this decreases the maximum on axis power of the array. Also, though gain and phase shading can alter the width of the main lobe and structure of the side lobes, it is not possible to mitigate grating lobes.

[004] The invention can be understood from a mathematical model of the line array. The acoustic pressure in the far field of a line array of N sources, each of which has directionality $H_s(\theta)$, is:

$$p(r,\theta,t) = \sum_{i=1}^{N} H_s(\theta) \frac{1}{r_i} e^{j(\omega t - kr_i)}$$

where θ is the angle, r_i is the distance from the ith source to the point in space $[r,\theta]$, t is time, ω is the frequency in radians per second, and k is the wave number where $\omega = kc$ and c is the wave propagation speed. The directionality of an omni directional source is 1 everywhere ($H_o(\theta) = 1$) so one can multiply any term in the equation above by the directionality of an omni and the acoustic pressure remains the same. Also the directionality of an individual source can be factored out of the sum:

$$p(r,\theta,t) = H_s(\theta) \left(\sum_{i=1}^{N} H_o(\theta) \frac{1}{r_i} e^{j(\omega t - kr_i)} \right)$$

In this form it can be seen that the directionality of an array of aligned sources is equal to the directionality of an array of omni directional sources multiplied by the directionality of an individual source. This is called the product theorem.

[005] For an array of omni directional sources in a straight line, each separated by distance d the directionality is:

$$p_{ao}(r,\theta,t) = \frac{1}{r} e^{j(\omega t - kr)} \left(\frac{\sin\left(\frac{N}{2} kd \sin(\theta)\right)}{\sin\left(\frac{1}{2} kd \sin(\theta)\right)} \right)$$

There are maxima in the absolute value of this function when:

$$|\sin(\theta)| = \frac{m\lambda}{d}$$

where m is any integer. The term $|\sin(\theta)|$ has a maximum of 1, so there will be more than one maxima when $d > \lambda$. These are called grating lobes.

[006] The present invention provides a horn structure for a line array of acoustic power sources that controls these undesirable grating lobes, as well as a method of designing such a horn. Referring to the product theorem for the directionality of an array of aligned sources, the invention uses horn loading to effectively choose a directionality for an individual source which is zero (or very small) in those directions where one expects grating lobes. Because horns achieve directionality by reflecting sound into a concentrated angle, the effect of this approach is to reflect sound that would otherwise contribute to the grating lobes, into the source's main lobe. The invention increases the highest operating frequency beyond that which the line array would normally be restricted due to the separation between acoustic power sources. It also increases the available on-axis power, and reduces the number of required acoustic power sources needed to obtain a desired power output by increasing the allowable size of each source. It is noted that the approach of the invention may be applied to any transducers of waves in linear media, including microphones, and transmitters and receivers of electromagnetic waves.

Summary of the Invention

[007] Briefly, in one aspect of the invention a horn is provided for horn loading multiple aligned acoustic power sources that are relatively widely spaced apart, that is, spaced apart by a wavelength or more at the highest operating frequency of the line array of sources. The horn includes a mouth end, a throat end and a flared section between the mouth end and throat end. The horn's throat end has a mounting flange to which the acoustic power sources of the line array of sources can be mounted, and which has a coupling port for each of the acoustic power sources. The acoustic power source coupling ports fix the spacing of the line array of power sources and couple the acoustic power generated by the sources to the flared section of the horn through throat openings associated with each acoustic power source. Grating lobe fins positioned in the flared section of the horn between the acoustic power sources extend from the throat opening associated with each power source toward the mouth end of the horn to a sufficient length for mitigating the predicted grating lobes produced by the line array to a desired level. The throat end of the horn is relatively short. It is sized to have dimensions on the order of a wavelength or smaller at the highest operating frequency; it also provides a suitable transition between the geometry of each acoustic power source mounted to the horn's mounting flange and the geometry of the throat opening associated with each these sources.

[008] In another aspect of the invention a loudspeaker is provided comprised of a multiple aligned acoustic power sources mounted to the throat end of a horn made in accordance with the invention.

[009] In still another aspect of the invention a method of designing a horn to suppress the grating lobes produced by multiple aligned acoustic power sources is comprised of choosing a

desired acoustic source for a line array of power sources, choosing a desired level of suppression for the predicted grating lobes for the line array, empirically designing the length of grating lobe fins for a single one of acoustic power sources to a achieve directional characteristic for the single source that suppresses off-axis acoustic power in the region of predicted grating lobes for the line array to the desired suppression level for the grating lobes, and providing a horn in accordance with the invention having grating lobe fins of a length designed for the single source, or longer.

Description of the Drawings

[0010] FIG. 1 is a front perspective view of a loudspeaker horn in accordance with the invention with an array of three aligned drivers mounted to the throat end of the horn;

[0011] FIG. 2 is a rear perspective view thereof without the drivers;

[0012] FIG. 3 is a front elevational view thereof;

[0013] FIG. 4 is a cross-sectional view thereof taken along lines 4-4 in FIG. 3, showing the drivers exploded away from the horn;

[0014] FIG. 5 is a cross-sectional view thereof taken along lines 5-5 in FIG. 3;

[0015] FIG. 6 is a rear elevational view thereof without the drivers;

[0016] FIG. 7 is side top plan thereof;

[0017] FIG. 8 is a representation of a sound field produced by an array of eight vertically aligned omni directional sources separated by less than a wavelength;

[0018] Fig. 9 is a representation of a sound field produced by an array of eight sources separated by exactly a wavelength;

[0019] FIG. 10 is a representation of a sound field produced by a single acoustic power source whose directionality has been designed to be as small as practical in the vertical direction where a

grating lobe of a vertical line array would be expected; and

[0020] FIG. 11 is a representation of a sound field produced by a vertical array of eight acoustic power sources, each of which is designed with the directionality characteristics of the single source shown in FIG. 10.

Detailed Description of the Illustrated Embodiment of the Invention

[0021] The loudspeaker horn shown in the drawings is designed for use with three vertically aligned drivers. The illustrated horn structure provides the desired control for mitigating grating lobes in the vertical direction while acting as a conventional horn in the horizontal direction. It should be noted that the invention is not limited to mitigating grating lobes in one direction only, and can be applied to any number of drivers.

[0022] Referring to FIGS. 1-7, the horn 11 includes a throat end 13 having a driver mounting flange 14, a mouth end 15 having flange 16, a flared section 17 formed by flared end walls 19, 21 and flared side walls 23, 25, and grating lobe fins 27, 29. Acoustic power is introduced at the throat end of the horn and is propagated into free space through the horn's mouth end in a characteristic distribution pattern about the horn's main propagation axis A. The grating lobe fins extend in the horizontal direction between side walls 23, 25 of the flared section of the horn and run substantially parallel to the horn's propagation axis between the flared section's end walls 19, 21.

[0023] The throat end of the horn extends from mounting surface 31 of driver mounting flange 14 to a throat opening 33 that opens into the flared section of the horn. The throat end provides a means for coupling drivers having a circular geometry that are mounted to the mounting flange to the throat opening which has a retangular geometry. Specifically, the

rectangular driver mounting flange has three aligned circular driver coupling ports 35, 37, 39 for receiving three aligned acoustic power sources in the form of drivers 41, 43, 45, which are mounted to the flange utilizing fastener and alignment pin openings 47, 49 in the mounting surface of the flange. It is contemplated that the drivers will be direct radiator type drivers, for example, a dome tweeter as illustrated in the drawings, mounted more than one wavelength apart at the loudspeakers highest operating frequency range. The drivers, which are mounted in alignment on the mounting flange, preferably matched drivers having substantially the same directionality characteristics so as to form a line array of drivers facing the same direction whose predictable grating lobe behavior under the product theorem mentioned above can be controlled in accordance with the invention.

[0024] The predicted grating lobes from the aligned drivers mounted to the horn's mounting flange 14 are controlled by grating lobe fins 27, 29. Each grating lobe fin is seen to have a base end 28, 30 that extends to the horn's throat opening 33 to effectively divide an otherwise elongated throat opening 33 into three aligned rectangular throat openings 51, 53, 55. Each throat opening 51, 53, 55 looks back into a circular to rectangular coupling chamber 57, 59, 61 formed by walls that form the throat end of the horn, such as walls 63 shown in FIG. 4 and walls 65 shown in FIG. 5. The size of the coupling chambers 57, 59, 61 should be on the order of a wavelength or smaller at the highest operating frequency of the loudspeaker.

[0025] The grating lobe fins 27, 29 should extend from the horn's throat opening 33 a suitable distance into the horn's flared section 17 to control the predicted grating lobes. For maximum control it is contemplated that the fins will extend all the way to the mouth end of the horn as illustrated in the drawings, however, it may be possible to use somewhat shorter

fins and still obtain adequate control. The minimum fin length would have to determined empirically for any given horn design. In general, fins of suitable length will intercept and reflect the acoustic power that would otherwise contribute to the grating lobes back toward the horn's main propagation axis A. In addition to mitigating the predicted grating lobes, this has the advantageous effect of increasing the available on-axis power.

[0026] The horn illustrated FIGS. 1-7 can suitably be fabricated as a molded plastic part. The angles and dimensions associated with the flared section 17, throat openings 51, 53, 55, and driver coupling chamber are arrived at empirically to achieve a desired frequency response and sound distribution pattern. It shall be understood that a horn having three aligned drivers is shown for illustrative purposes only and that a horn in accordance with the invention could made to accommodate any number of aligned drivers. The addition of a driver to the line array would require that a driver coupling port and chamber, and a grating lobe fin be added to the horn.

[0027] The following is an exemplary application of the loudspeaker horn of the invention used to horn load a line array of drivers that provide the high frequency of full range speaker system having high and low frequency drivers in a speaker box with crossover circuit:

High frequency drivers	--	horn loaded line array of one inch metal dome drivers (tweeters)
Physical dimensions of horn	--	driver coupling port diameter = 1inch +
	--	driver spacing = 1.30 inches
	--	length of driver coupling chamber = 0.50 inches
	--	overall length of horn from driver mounting surface = 2.42 inches
	--	throat openings (51, 53, 55) = 0.826 x 0.50
	--	mouth of horn (without flange) = 5.33 inches
	--	angle between flared section end walls (19, 21) and grating lobe fins = 24.3 degrees

Low frequency drivers	--	two 5 inch cone drivers
Speaker box dimensions	--	23.20 inches wide x 7.20 high x 8.50 inches deep

The above loudspeaker design parameter can achieve an operating frequency range of 60Hz to 18kHz without the high frequency driver line array component of the loudspeaker introducing significant grating lobes to the polar response characteristics of the loudspeaker at high frequencies.

[0028] FIGS. 8 through 11 show acoustic power distribution patterns in an X-Y plane for various arrangements of acoustic power sources and illustrate the creation of grating lobes as a function of the spacing between sources and the control of grating lobes by controlling the directionality of individual sources within an array.

[0029] FIG. 8 is a sound field representation for an array of eight vertically aligned omni directional sources separated by less than a wavelength. In this arrangement it can seen that the array is highly directional with no grating lobes. Such arrays would require small acoustic power sources spaced close together (less than a wavelength).

[0030] FIG. 9 shows the directionality of an array of eight sources separated by exactly a wavelength. Here the array is seen to produce vertical lobes (in the direction of the y-axis), which are the grating lobes. These grating lobes are equal in magnitude to the main lobe (in the direction of the x-axis), and cannot be mitigated by gain or phase shading.

[0031] FIG. 10 shows the directionality of a single acoustic power source (a single speaker) whose directionality has been designed to be as small as practical in the vertical direction where a grating lobe of a vertical line array would be expected. Using a single ascoustic source the length

of the grating lobe fins for the horn of the invention, such as horn 11 illustrated and described above, can be determined based of the degree of suppression desired for the grating lobes.

[0032] FIG. 11 shows a vertical array of eight sources (speakers), each of which is designed with the directionality characteristics of the single source shown in FIG. 10. The directionality characteristics are achieved using the horn of the invention above described wherein acoustic power in any grating lobes produced by the array would be redirected into the sources main lobe. In the array in FIG. 5 the sources are spaced apart one wavelength where significant grating lobes would normally be expected. However, it can see that grating lobes in the FIG. 5 array have been significantly reduced.

[0033] While the present invention is described in considerable detail in the foregoing specification, it is not intended that the invention be limited to such detail, except as necessitated by the following claims.